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Stress Analysis of FLARE Liquid Argon Tank

Bob Wands

Introduction and Summary

The liquid argon tank proposed for FLARE is 130 feet in diameter and 108 feet tall. It will be constructed as a weldment of 9% nickel steel plate in fourteen courses, each eight feet in height, excepting the last course, which is four feet in height. Plate thickness will vary with hydrostatic head, being thickest at the bottom and thinnest at the top.

Large tanks such as this are well-known to the liquefied gas industry. However, the FLARE wire arrays, by reacting the wire tension against the tank wall, impose out of plane loads which are not seen in the industrial applications.

The purpose of this analysis is to determine the plate thicknesses necessary to withstand the hydrostatic and wire tension loads while meeting the requirements Section VIII, Div. I of the ASME Boiler and Pressure Vessel Code.

The results show that the maximum plate thickness is 2.5 inches; the minimum thickness is 0.5 inches. Maximum stress intensity is less than the allowable of 23,700 psi, and the safety factor on buckling under the out-of-plane loads is greater than 5.0

Allowable Stresses and SF on Buckling

The ASME Section VIII Div. I maximum allowable stress in tension for welded SA-553 9% nickel steel plate is 23.7 ksi. This is consistent with the value used in non-Code industrial practice.

The minimum safety factor on buckling is not specified, but experience with Code calculations indicates that a minimum factor of four is typical.

Loading

The density of saturated liquid argon at atmospheric pressure is 87.4 lbs/ft^3. Assuming that the tank is filled to the maximum height of 108 feet with this liquid, the resulting pressure on the bottom of the tank is 108(87.4)/144 = 65.55 psi. In addition to this hydrostatic pressure, the tank will also have a slight overpressure of 1.5 psi to ensure positive venting and guard against contaminants.

For this analysis, a maximum pressure of 70 psi is used.

The location and magnitude of wire loads, which react with the roof, floor, and wall of the tank, and the roof dead weight, which rests on the wall, are per R. Silva.

These loads, as they were applied to the ¼ symmetric finite element model, are shown in Fig. 1

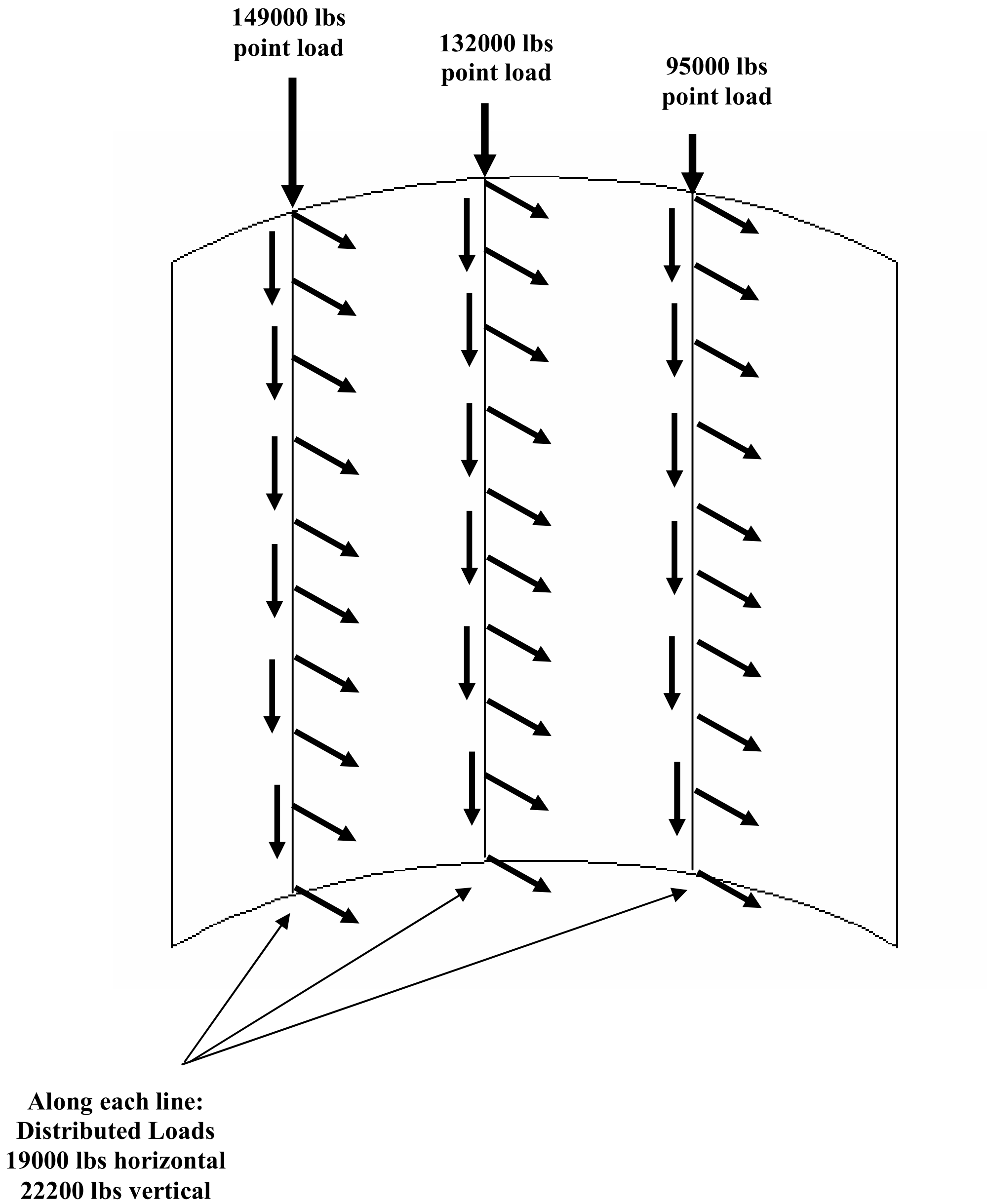


Figure 1. Location and Magnitude of Wire and Roof Loads (1/4 model)

Initial Plate Thickness Calculations – ASME Code

From ASME Section VIII, Div. 1, UG-27(c)(1), the thickness of a cylindrical shell under internal pressure shall be no less than

$$t = PR/(SE-0.6P)$$

where t = thickness of cylindrical shell
P = internal pressure
R = mean radius of shell
S = maximum allowable stress in tension for material
E = weld efficiency

If $R = 780$ in, $P = 70$ psi, $E = 1$ (fully inspected butt welds), and $S = 27.3e3$ psi, then the maximum thickness at the bottom of the tank is

$$t = 70(780)/(23700(1)-0.6(70))$$

$$t = 2.31 \text{ inches}$$

For this analysis, a maximum thickness of 2.5 inches will be used.

Applying the same calculation to the remaining courses gives the thicknesses shown in Table I. Near the top of the tank, where hydrostatic pressure is very low, the thickness was determined by the minimum plate thickness customarily used in a vessel of this size.

Table I. Course Thicknesses for FLARE Tank

Course	Mean Height from Bottom of Tank - ft	Thickness - in
1	4	2.50
2	12	2.25
3	20	2.00
4	28	2.00
5	36	1.75
6	44	1.50
7	52	1.50
8	60	1.25
9	68	1.00
10	72	1.00
11	80	0.75
12	88	0.50
13	96	0.50
14	102	0.50

Finite Element Model

A ¼ symmetric finite element model was created using a mesh of 7500 four-node shell elements. This model is shown in Fig. 2. The detail of connection between the vertical walls and the base is extrapolated from industrial practice, with a 0.25 inch thick floor welded to an 8 by 2.5 inch annular ring, which is in turn welded to the lowest course.

The total weight of 9% nickel steel is 2.6e6 lbs.

Loading consisted of a linearly varying pressures (0 psi at the top of the tank, 70 psi at the bottom), plus the line and point loads of the wires and roof shown in Fig. 1.

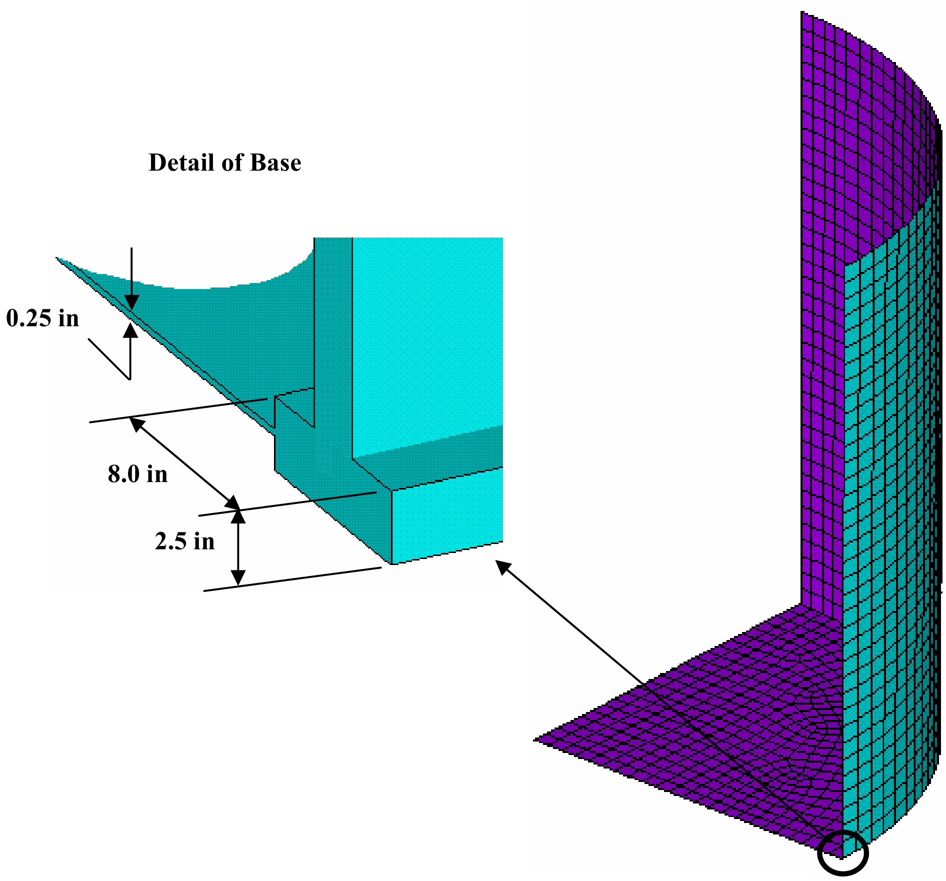


Figure 2. Finite Element Model of FLARE Tank

Results

Stresses and Deflections Under Wire and Roof Loads

The roof and wires will be installed before the tank is filled with liquid argon. It is therefore necessary to ensure that the tank stresses under this loading are admissible, and that the margin on buckling is sufficient, when the hydrostatic pressure (which tends to stress the tank in opposition to these loads) is absent.

Fig. 3 shows the radial deflections under the non-hydrostatic loads. The maximums occur in the thin course near the top of the tank, and are 1.24 inches inward, and 1.14 inches outward. These deflections can be minimized by either thickening the upper courses, or reinforcing the lip of the vessel.

Fig. 4 shows the maximum stresses in the vessel under the non-hydrostatic loads. The maximum stress does not exceed 5300 psi, which is well under the allowable stress of 23700 psi.

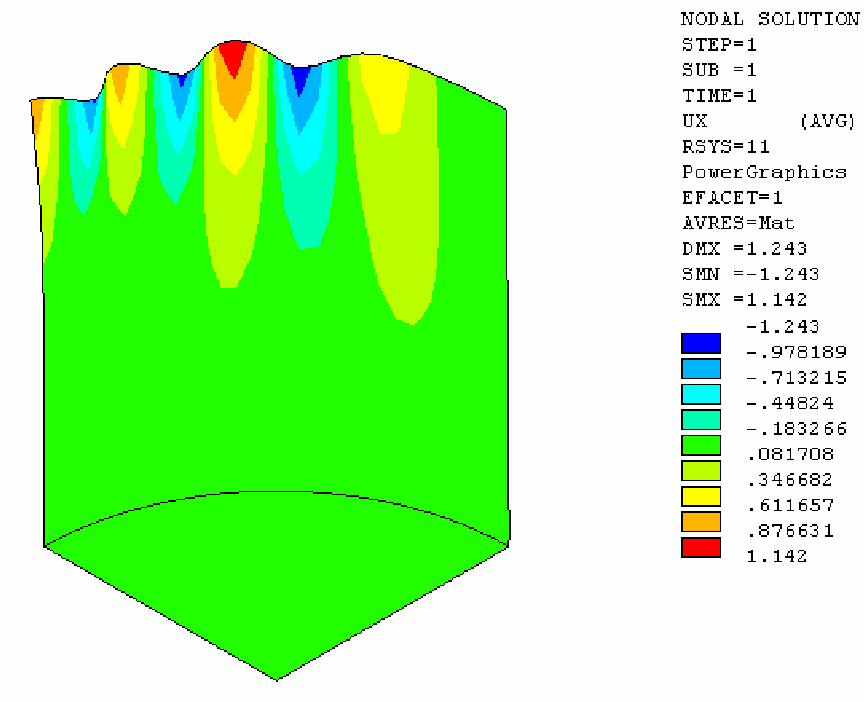


Figure 3. Radial Deflections Under Roof and Wire Loads Only

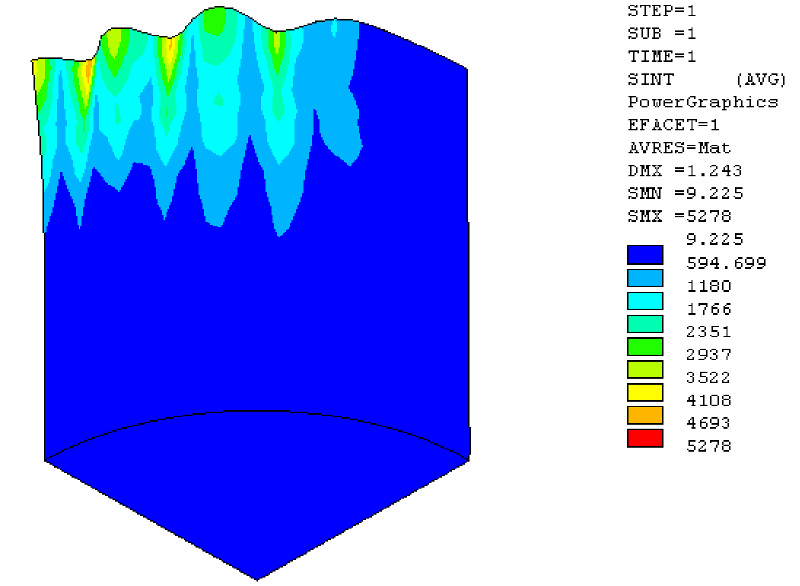


Figure 4. Stress Intensity Under Roof and Wire Loads Only

<u>Stability Against Buckling Under Roof and Wire Loads Only</u>

For cylindrical shells under uniform external pressure (i.e., a pressure that produces compressive hoop stresses), the ASME Code provides explicit rules to ensure adequate margin against shell buckling. In this case, however, while the loads are normal to the shell and produce compressive hoop stresses, they are discrete, not uniform, and no Code rules are available. Therefore, under U-2(g) of Section VIII, Div. 1, alternate means may be used to perform the buckling evaluation.

For this analysis, two methods are available. The first, and simplest, is the numerical extraction of eigenvalues and eigenvectors from the governing stiffness matrix. This is essentially the equivalent of Euler column buckling applied to thin shells. The second method is a full non-linear analysis, in which the load is incremented slowly until the stiffness drops suddenly, indicating instability and imminent collapse.

The results of these approaches are shown in Figs 5 and 6. Eigenvalue buckling predicts that the first collapse mode could occur at a load which is 5.4 times greater than the load applied to the model; the second mode occurs at a slightly higher load factor of 6.5. The nonlinear approach predicts a higher load factor of 7.5.

The lowest predicted load factor of 5.4 is well above the required minimum load factor of 4.

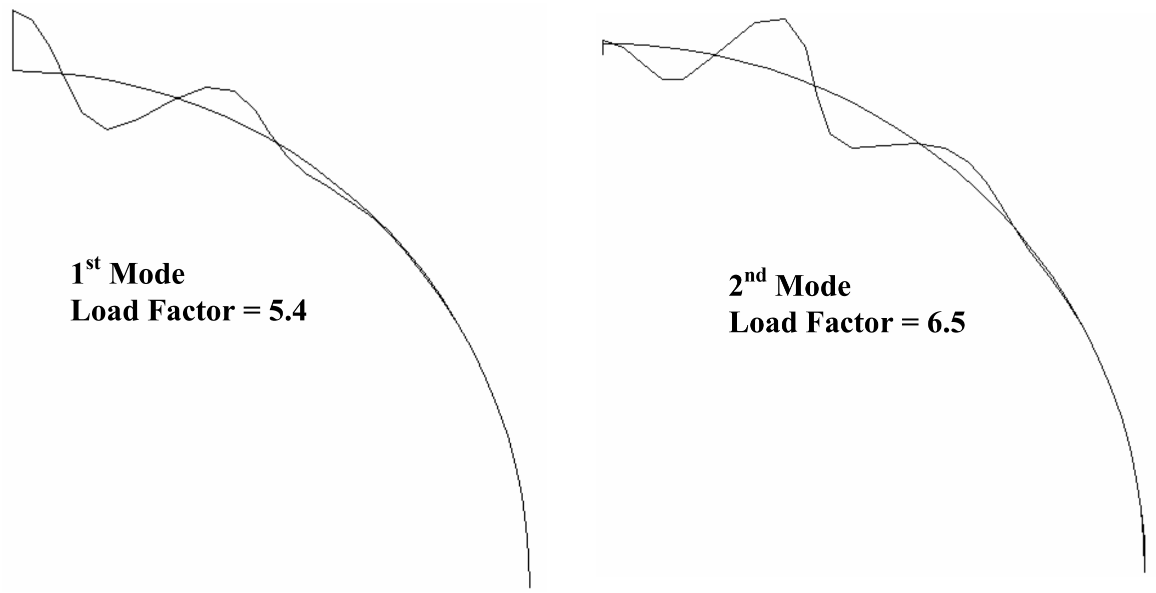


Figure 5. Buckling Modes and Load Factors from Eigenvalue Approach

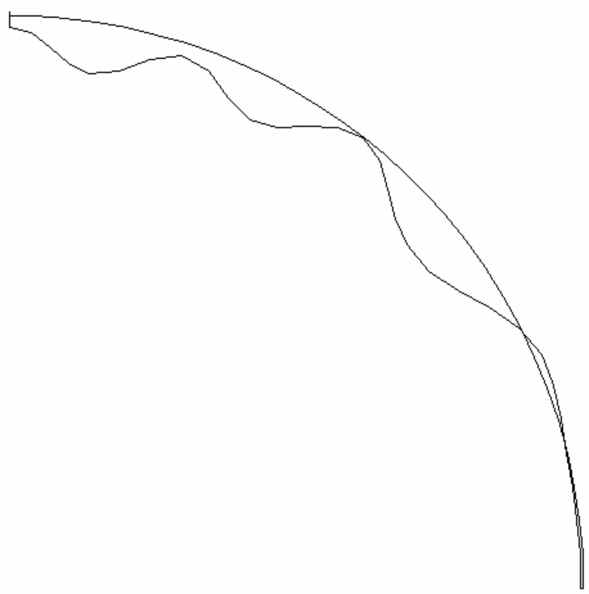


Figure 6. Buckling Mode and Load Factor from Non-linear Analysis

Stresses and Deflections Under All Loads

The radial displacements of the tank under all loads are shown in Fig. 7. At the point of wire load application they are a maximum of 1.27 inches inward. As mentioned previously, this displacement can be easily controlled by either increasing the thickness of the top courses above their current 0.5 inches, or by stiffening the lip of the opening circumferentially. The latter solution may be a natural consequence of a designing a realistic closure between the tank and its roof.

The stress intensity in the tank under pressure, wire, and roof loads is shown in Fig. 8. A plot of the stresses as a function of tank height is shown in Fig. 9. Stresses are at the mid-thickness of the shell elements, and do not exceed 23.5 ksi.

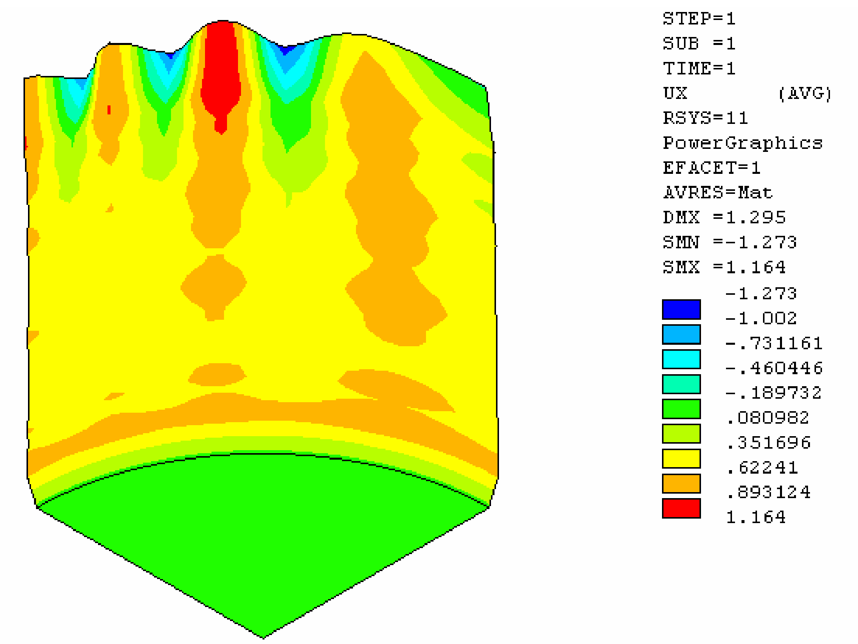


Figure 7. Radial Deflections of Tank Wall Under Pressure, Wire, and Roof Loads

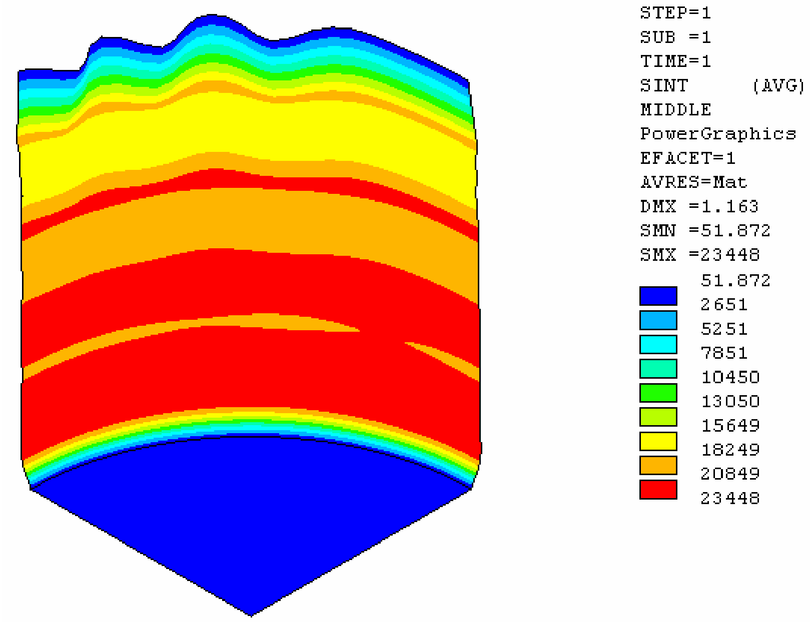
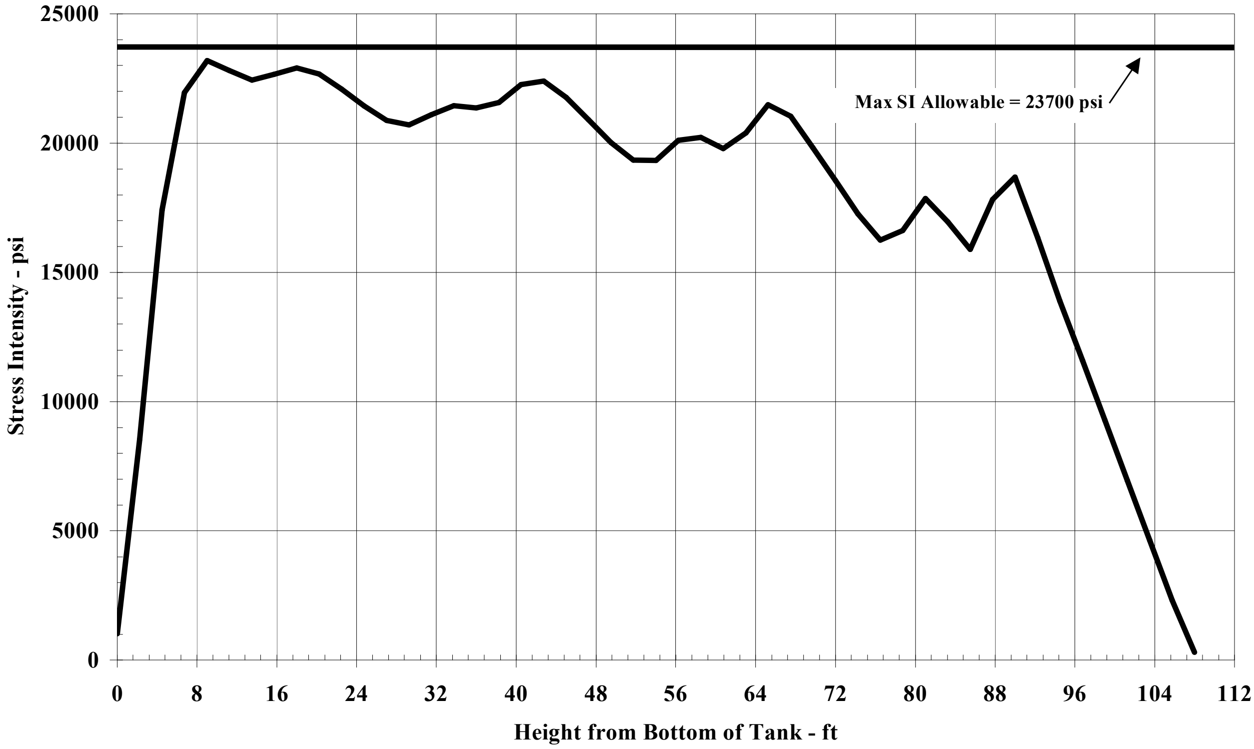


Figure 8. Mid-plane Stress Intensity in Tank – Pressure, Wire, and Roof Loads

Figure 9.
Midplane Stress Intensity as Function of Height in FLARE Tank - All Loads



Conclusion

The FLARE tank does not appear to offer challenges greater those of any other commercial LPG storage tank of similar dimension. The course thicknesses given here are within the range of those commonly used in industrial practice, and a design based on head pressure alone has enough inherent strength to resist the unusual out-of-plane wire reactions.

Further analysis is required in several areas (heat transfer, thermal contraction, head/tank closure, truss roof design, etc.) but the basic concept as presented here appears sound.